THE GEOLOGY OF THE HIGHLAND BORDER

FROM TAYSIDE TO NORANSIDE.

by

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VOLUME I.

I N D E X.

SECTION I.

INTRODUCTION.

The area examined in the course of this investigation comprises parts of Perthshire and Forfarshire fringing the Grampians and Strathmore from Stenton on the Tay, two-and-a-half miles east of Dunkeld, to Paphrie Burn the most southerly tributary of the West Water which joins the North Esk. It is represented on a scale of one inch to a mile on Sheets 48, 56, and 57 of the Ordnance Survey of Scot--land. The field-mapping of over one hundred and thirty square miles was carried out on a scale of six inches to a mile.

The district described is approximately parallel to the Highland Boundary Fault, the north-eastern limit geologically and geographically of the Central Valley of Scotland. To the north of the fault zone is a highly folded series of schistose grits, phyllites, clay slates, and quartzites — the Dalradian Schists — together with a varied suite of intrusive/

intrusive igneous rocks. To the south are sandstones, conglomerates, and volcanic rocks of Lower Old Red Sandstone age, with a steep dip to the south-east, constituting the northern limb of the great Strath--more syncline. Within the fault area occur Lower Old Red Sandstone rocks, in the main closely akin to those to the south, and in addition a belt of serpentine.

SECTION II.

PHYSIOGRAPHY.

The diversity of rock types and structures within the area is reflected in its superficial characteristics, which lend themselves readily to a tripartite division. North-west of the Highland Boundary Fault zone, where schistose rocks abound, is the southern margin of the dissected plateau of the Grampian Mountains displayed as a range of peaks which includes Silverside (1041), Deuchany Hill (1670), Knockton (1605), Creigh Hill (1630), Cat Law (2196) and St. Arnold's Seat (1611). The major valleys cut through the range are the Tay Valley, Glenericht, Glenisla, Glen Prosen, Glen Clova, Glenquiech and Glenogil. The topography of so ancient a rock mass, which has served presumably often as a land area in the past, is thoroughly mature, and in particular the work of the great Pleistocene ice sheets can be traced in the gently curved outlines of both hollow and hill.

To the south-east, within the Fault zone,

is/

is a belt of rounded hills with an average height of 1,000 feet and orientated in a N.E. - S.W. direction. These are composed mainly of Lower Old Red Sandstone conglomerates and more rarely of acid igneous rocks, while the low ground coincides with the disposition of the finer-textured sediments and the generally basic lava flows of Lower Old Red Sandstone age. Among the conglomerate hills are Balduff Hill (1394), Knock of Formal (1158), The Carrach (1164) and Ascreavie Hill (922). Acid igneous rocks form Tamhingan (615), Lochbraes, Lintrathen (703), Aucharroch Hill (1033) and the Knock of Cortachy (922). There is a most striking contrast between the topo--graphical prominence of Carboniferous lava flows of the Central Valley of Scotland or the Old Red Sand--stone extrusive rocks of the Sidlaws or the Ochils, and the insignificance of such lavas along the Highland Border.

The third division, still further to the south-east, is composed of finer grained sediments of Lower Old Red Sandstone times and its surface, which is in the main devoid of any noteworthy topographical relief/

relief except that due to localised occurrences of Glacial deposits, slopes down gradually to the centre of the Howe of Angus and its greater continuation, Strathmore.

While the junction of the first and second divisions is also that of the two main rock groups comprising them, the southern boundary of the second division is a fault which truncates different members of the Old Red Sandstone sequence at different places, so that there is no fundamental connection between it and the variations of surface relief on either side of it. The revised mapping of the more southerly Highland Boundary Fault places that line of disloca--tion on the edge of Strathmore on Tayside while it passes north of the conglomerate hills of Glour o'er Him, Alyth Hill, Clunehill, and the Hill of Ogil which lie well above the southern valley.

The rivers flow in a general south-easterly direction through the first zone; in the second there is a tendency for deflection eastwards along the axis of folding of the rocks there; in the third/

third there is much meandering through flood planes and glacial accumulations, together with striking examples of river capture by tributaries of the Tay into which the waters of the Ericht-Isla river systems now drain. In their passage the rivers demonstrate the relative values of the different rocks in the formation of scenery, for numerous gorges and water--falls are associated with conglomerates at the Slug of Achrannie, Loups of Kenny, Den of Airlie, and Craighall Gorge, and with igneous masses at the famous Reekie Linn, Craighead, and Carity Den.

The lochs of the district, of which there is fully a score, appear to be the remnants of a much more extensive system, evidenced by the widespread occurrence of alluvial flats, and are probably directly connected with the wane of the Great Ice Age. Some of the existing sheets of water have been extended artificially to supply the needs of neighbouring towns; Loch of Lintrathen (Dundee), Den of Ogil Reservoir (Forfar), Loch Benachally (Blairgowrie).

SECTION III.

PREVIOUS INVESTIGATIONS.

A. Within the area.

1820. Ami Boué,

"Essai Géologique sur l'Écosse." p. 54.

1824. John MacCulloch,

"On the Limestone of Clunie, in Perthshire, with remarks on Trap and Serpentine." Edin. Journal of Science, Vol. I., p. 1.

1825. Charles Lyell,

"On a Dike of Serpentine, cutting through Sandstone, in the County of Forfar." Edin. Journal of Science, Vol. III., p. 112.

1845. The New Statistical Account of Scotland, Vol. X., "Perth". p. 1112.

1863. J. Nicol,

"On the Geological Structure of the Southern Grampians." Q. J. G. S., Vol. XIX., p. 180.

1883. Sheet 48, Map of the southern part of the area on a scale of 1 inch to a mile, by H. M. Geological Survey of Scotland.

1884. Sheet 57. Map of the northern part of the area, similar to that in previous reference.

1885. J. W. Judd,

"On the Tertiary and older Peridotites of Scotland." Q. J. G. S., Vol. XLI., p. 354.

1886/

1886. J. Durham and J. W. Judd,

"Volcanic Rocks of the North East of Fife." Q. J. G. S., Vol. XLII., p. 418.

1888. J. J. Teall,

"British Petrography." pp. 128, 286.

1895. Sheet 56. Map of the central part of the area on a scale of 1 inch to a mile, by H. M. Geological Survey of Scotland.

1897. A. Geikie,

"The Ancient Volcanoes of Great Britain." pp. 277, 292, 293, 304, 305, 311.

1899. J. A. R. Macdonald,

"The History of Blairgowrie." p. 21.

1901. G. Barrow,

"On the Occurrence of Silurian (?) Rocks in Forfarshire and Kincardineshire along the Eastern Border of the Highlands." Q. J. G. S., Vol. LVII., p. 328.

1901. M. F. Heddle,

"The Mineralogy of Scotland." Vol. 2,p.133.

1908. P. Macnair,

"The Geology and Scenery of the Grampians."

1912. G. Barrow,

"On the Geology of Lower Dee-Side and the Southern Highland Border." Proc. of the Geol. Assocn. Excursion to the East of Scotland, p. 274.

B. In adjacent areas.

1877. R. L. Jack and R. Etheridge (Junr.),

"On the Discovery of Plants in the Lower Old Red Sandstone of the Neighbourhood of Callander."
Q. J. G. S., Vol. XXXIII., p. 213.

1905. A. Du Toit,

"The Lower Old Red Sandstone Rocks of the Balmaha-Aberfoyle Region."
Trans. Geol. Soc. Edin., Vol. VIII.,p. 315.

1908. H. G. A. Hickling,

"The Old Red Sandstone of Forfarshire, Upper and Lower."
Geol. Mag. Vol. V., p. 396.

1911. R. Campbell,

"Preliminary Note on the Geology of S.E. Kincardineshire."
Geol. Mag. Vol. VIII., p. 63.

1912. R. Campbell,

"The Geology of South-East Kincardineshire."
Proc. of the Geol. Assocn. Excursion to the East of Scotland, p. 295.

1912. H. G. A. Hickling,

"On the Geology and Palaeontology of Forfarshire."
Proc. of the Geol. Assocn. Excursion to the East of Scotland, p. 302.

1913. R. Campbell,

"The Geology of South-Eastern Kincardineshire"
Trans. Roy. Soc. Edin. Vol. XLVIII., p. 923.

1913./

1913. A. Jowett,

"The Volcanic Rocks of the Forfarshire Coast and the Associated Sediments."
Q. J. G. S. Vol. LXIX., p. 459.

1917. T. J. Jehu and R. Campbell,

"The Highland Border Rocks of the Aberfoyle District."
Trans. Roy. Soc. Edin. Vol. LII., p. 175.

SECTION IV.

THE DALRADIAN SCHISTS.

No detailed investigation of the Dalradian schists was attempted, but, as they form the boundary of the Lower Old Red Sandstone rocks along the north-western flank of the district and in certain localities serve as the floor upon which these younger rocks accumulated, their general characteristics were noted. Lithologically they fall into two well-defined groups, a set of strongly foliated, rather fine-grained, schistose grits, and a less extensively exposed series of light silver-grey to dark grey phyllites, readily fissile but too crumpled to serve as roofing material, although the outcrop has been quarried in several places.

While the structure planes of the rocks, sometimes foliation and sometimes bedding, are often vertical, there is most commonly a steep inclination of from 40^{o} to 70^{o} in a direction between north and north-west. Towards the extreme north-east, beyond Cortachy/

Cortachy, the inclination is rather to the south and south-east. Folds are not so frequently revealed as might be expected, the only locality where the tops of flexures can be seen being in the Burn of Water--sheal. In that section the schistose grits are also faulted, the dislocation probably being to some extent responsible for the preservation upstream of a small outlier of Lower Old Red Sandstone lavas.

SECTION V.

THE HIGHLAND BORDER ROCKS.

A. Field Characters.

The pioneer work of G. Barrow determined the occurrence of two suites of rocks, named from the locality of their outcrops the Highland Border Rocks, and consisting of a lower Jasper and Green-Rock Series thought to be of Arenig age, and an upper Margie Series of conglomerate, grits, shales and limestone of younger Silurian age.* In Kincardineshire (1909) R. Campbell showed that many of the Green-Rocks were spilitic lavas and that the overlying cherts and cherty mudstones con--tained a fossil assemblage strongly suggestive of Upper Cambrian age.** The later work of T. J. Jehu (1912) and R. Campbell in the neighbourhood of Aberfoyle brought to light further fossil remains and indicated an Upper Cambrian, or Cambro-Ordovician Transition Series age for the lower group, and an Upper Ordovician/

* "On the Occurrence of Silurian (?) Rocks in Forfar--shire and Kincardineshire along the Eastern Border of the Highlands", Q. J. G. S., Vol. LVII., 1901, p. 334.

**."The Geology of South-Eastern Kincardineshire", Trans. Roy. Soc. Edin., vol. XLVIII., 1913, p. 927.

Ordovician age for the Margie Series.*

To the north-east of Cortachy, Barrow mapped a long strip of Margie rocks, but of them no description has ever been published. They occur as a narrow belt from the north-east end of the Knock (Cortachy), and stretch north-eastwards parallel to the main Highland Boundary Fault as far as the present investigation extended, (Pl. I., fig. 1.). They consist in the main of grits, the constituents of which are somewhat flattened grains of white and blue quartzes, and turbid felspars, rendered coherent by a ferruginous cement which weathers to a bright ochrous colour. The grits are fairly resistant to weathering and stand out as little craigs along the north side of several of the marginal drainage channels which follow the fringe of the Grampians.

In the extreme north-east the grits outcrop along the banks of the Cruick Water above Afflochie for a distance of a quarter of a mile, beyond which a series of phyllites is exposed. Both phyllites and grits dip southwards at about 65^{o}.

To/

* "The Highland Border Rocks of the Aberfoyle District" Trans. Roy. Soc. Edin. Vol. LII., 1917, p. 193.

To the south-west, solid rock is revealed in the road floor beside Auchnacree. The beds dip 75° in a direction S. S. E., the series beginning with grits of the usual type, overlying which is about thirty-five feet of green and grey shales. Then follow two feet of reddish-tinted soft sandy shales, which pass under blue micaceous shales of which some twelve feet are exposed before the sequence is lost under road metal.

Between Auchnacree and Glenley to the south--west there are several exposures of Margie Grits with a general north-westward dip. Associated with them and included in the Margie Grits group as shown by the colour on the Geological Map (Sheet 57), is an outcrop on the southward bend of the road halfway between the two places, where a few feet of well-bedded yellow sandstones flank the roadway. In some parts of the outcrop there is good current bedding, but the general disposition of the rock cannot be far from horizontal. The Lower Old Red Sandstone rocks to the south all have a pronounced red colour and a fairly steep dip. The light yellow colour is common to many of the Margie Grits in the vicinity, but the fineness of texture and lowness/

lowness of dip are at variance with their characteristic development, nor can I find any reference to current bedding in connection with them in other localities. H. G. A. Hickling has described false-bedded sandstones from the Upper Old Red Sandstone Series of Forfarshire,* and R. Campbell alludes several times to such structures in similar Upper Old Red Sandstone rocks in Kincardineshire.** It is possible that there is here preserved a small remnant of rocks of that age, lying unconformably upon a Margie basement.

An interesting new find is a section in the R. Prosen, above Prosenhaugh. Beyond the northern boundary of the serpentine belt there is a series of beds with a very steep dip towards the N. N. W., so that unless the sequence is complicated by isoclinal folding the lowest beds occur at the south end where the first exposures are very fine schistose grits. Above lies a group of black graphitic shales, about 90 feet thick, but the beds are highly disturbed and show unmistakable/

* "The Old Red Sandstone of Forfarshire, Upper and Lower", Geol. Mag. Vol. V., 1908, p. 403.

** "The Geology of South-Eastern Kincardineshire" Trans. Roy. Soc. Edin. Vol. XLVIII., 1913, p.955.

unmistakable signs of movement. As the foliation of these rocks is roughly parallel to the original bedding planes, a close search was made for fossils, but although many suggestive marks were found in no case was it possible to be certain that they were of organic origin. Empty cavities are common, lined with carbo-naceous material, within which frequently there was a layer of calcite. The interior of many of the cavities showed structures which may have been the relics of some organism. The shales contain numerous nodules of marcasite and iron pyrites.

The next bed in the sequence is a layer of compact dark grey chert about a foot in thickness. The succeeding phyllite bands have a steep dip in a direc-tion about thirty degrees north-eastward of that of the shale-chert group, but beyond is a great mass of schistose grits dipping in the same direction and with the same inclination as the shale-chert beds. It may be that the variation of dip shown by the phyllites indicates a plane of dislocation along the southern boundary of the Dalradian Schists.

B. Petrology.

The grits consist mainly of cracked and shattered quartz fragments, almost invariably showing strain shadows. The rim of each rounded grain is very finely granulitised, the alternate minute serrations being occupied partly by pulverised matrix material and partly by sheaf-like aggregates of strongly polarising muscovite, while the intervening ones, no matter how slender they are, consist of quartz in perfect continu--ity with the grain. There is much acid plagioclase present, mainly oligoclase, the twin lamellae of which are split, bent, separated, and broken in many cases. The felspar shows the granulitisation already described but to a less degree than the quartz. This "chevaux de frise" structure has been described from many schistose grits, and Greenly found a similar develop--ment around the grains of the Harlech Grits.* There the sheaves which penetrate the quartz are sometimes chlorite, sometimes green biotite or hornblende. In the/

* Trans. Geol. Soc. Edin., Vol. VII., 1897, p. 254.

the present case the material is occasionally chloritic but is much more commonly muscovite. There is shown the same radiate disposition of the minerals which penetrate the quartz and felspar grains indicative not of shearing stresses, which would have produced a parallelism of the scaly minerals, but of recrystallisa--tion probably in response to pressure.

While microcline does occur, it is only in small amount. Biotite is apparently represented by tabular and streaky masses of black iron oxide, which occasionally shows good hexagonal forms. Elongated areas of pleochroic green scaly chlorites are probably pseudomorphous after biotite but with a different decomposition history. Clastic muscovite is present in great abundance as elongated flakes. The minor constituents are small tourmalines, zircons, and specks of black iron oxide.

Recognisable rock fragments fall into three groups. Quartz and oligoclase occur occasionally in contact, the product of the decomposition of some relatively acid plutonic rock. Quartzite is present in the form of quartz mosaics with no cementing material.

The/

The areas of green chloritic minerals, sometimes with a curious circular "spotted" design may represent the wastage of basic volcanic rocks. Similar material has been noted frequently among the Old Red Sandstone tuffs.

Carbonate cement is present in fair amount, the ferruginous material having sometimes given place to the oxide with the formation of black streaks envel--oping the grains of quartz, felspar, etc.

The graphitic shales of the Prosen section are composed of very fine elongated quartz grains, separated by streaks of black material which is partly carbonaceous and partly ferruginous. Strongly polarising sericitic mica is widely disseminated through--out the rocks. Deformation by shearing movements is clearly seen, and strings of broken fragments from particular lamellae can be traced across the microscope sections. Some "augen" structure around quartz grains can be observed in most sections. If the original quartz was entirely crystalline, it would seem that either the shearing or infiltration of water or perhaps both together had contributed to replace it by an almost isotropic variety.

The/

The chert band overlying the shales consists of finely granular silica, some showing the normal extinction of quartz and some with the wavy extinction of crypto-crystalline chalcedony. In veins and strings throughout the sections occur mosaic groups of quartz, devoid of strain shadows.

Set in this siliceous matrix are innumerable tiny rhombs of calcium and of ferrous carbonate. Only the outer rim of these shows regular crystalline form, the cores being aggregates of minute granules, often clustering about a speck of black iron oxide. Very tiny flakes of muscovite are of widespread occurrence, together with hair-like needles of rutile which are only visible with the aid of a high power objective. Minute fragments of brownish pleochroic biotite have been noted in a few cases, (Pl. XIX., fig. 3.).

C. Conclusions.

The absence of fossils precludes the possibi--lity of assigning these Highland Border rocks directly to a place in the stratigraphical sequence, but we can compare them with lithologically similar rocks occurring along the fault zone, whose age has been determined/

determined by the fortunate preservation of fossils.

The black shale-chert rocks most closely resemble the lower of the two Highland Border groups, which is of Upper Cambrian or Cambro-Ordovician Transition Series age. In their monograph on the Highland Border rocks of the Aberfoyle area, T. J. Jehu and R. Campbell state (p. 182) with reference to the Upper (Margie) Series that the shales there "are accompanied by limestone, never by cherts or cherty shales and mudstones." In the Basement Breccia of the Margie Grit Series they describe the occurrence of numerous fragments of cherty shales similar to those of the underlying Black Shale and Chert Series, and mention the presence of muddy chert with rhombs of ferrous carbonate, (p. 183).

It will thus be seen that the Prosen sequence follows that given by G. Barrow for the rocks immediately overlying the Green Rocks further north.*

Fine Grit.

Fine Shale, cleaved.

Jasper (altered radiolarian chert?).

Green Rocks.

* Q. J. G. S., Vol. LVII., 1901, p. 334.

As the Prosen section commences with fine grits apparently dipping below the shales, which in their turn are succeeded by the chert, there would seem to be an inversion of the normal order, owing to an overfold.

The coarse grits mapped as Margie Grits seem to be lithologically similar to those described from Kincardineshire and the Aberfoyle district.

SECTION VI.

ROCKS OF LOWER OLD RED SANDSTONE AGE.

A. Volcanic Rocks.

B. Conglomerates.

C. Sandstones etc.

A. Volcanic Rocks.

On the maps of the Geological Survey of Scotland the numerous lava flows are all grouped together as porphyrites (andesites), and one colour is employed to designate them. In the course of the field mapping it was obvious from the hand specimen characters that different types of rock were present, and the microscopic examination of a great number of rock sections has formed the basis of the subdivisions described in the succeeding portion of this paper. Most of the lava-form rocks may be termed basalts and andesites, the latter being in some cases acid types but more commonly basic. In colour they vary from grey to blue and black. A certain amount of decomposition is nearly always present, the rocks then/

then presenting a greenish to grey tint with sporadic areas of dark iron oxide. Porphyritic structure may or may not be visible. Fluxion banding is generally difficult to see and columnar jointing is exceptional. On the other hand the development of platy jointing is widespread: it seems to be at right angles to the flow surface in the thicker masses and parallel to that direction in the thinner ones, but this is pro--bably by no means true in every case. Vesicularity on a small scale is almost universal: in some cases the steam holes are minute and most abundant, in others the vesicles near the upper surface of the lava are fully three inches long and as large as hens' eggs. The most common infilling material is calcite but agates occur plentifully in some of the lavas, and are usually reddish or yellowish in colour. Thin veins and streaks of sediments are frequently associated with some of the flows.

The somewhat peculiar rock known as the Lintrathen porphyry is without doubt the most striking member of the igneous suite from the Highland border area. Its resistance to weathering and denudation is/

is in marked contrast to the behaviour of most of the igneous material, and where any considerable mass of it is exposed, a hill feature is the result. At a little distance its bright reddish colour and marked fluxion structure attract attention, and a closer inspection shows the rock to consist of glistening crystals of quartz, less conspicuous plagioclase, and flashing plates of biotite set in a compact deep red groundmass. As will be indicated in detail later, this rock both microscopically and chemically is a dacite.

The dacite has been mapped hitherto as an intrusion and as the work of the present investigation progressed and new exposures of it were discovered along both limbs of the elongated syncline established by the revision, it became evident that the rock was in the form of a sheet. While contacts with the overlying and underlying rocks were difficult to find, as the dacite is invariably the more resistant mass, the exposures in the Isla gorge yielded interesting results. On the south bank, due north of Mains of Craigisla, the dacite dips steeply under a flow of biotite-andesite/

biotite-andesite and, although the sequence cannot be demonstrated in one outcrop, is apparently separated from it by a band of tuff, (Pl. IV., fig. 1.). Half-a-mile to the east on the north bank of the deep pool -- the Devil's Punchbowl -- below Easter Peel, there is a much better exposure (Pl. II., figs. 1 and 2). Near the water level the dacite dips to the N.N.E. at a fairly steep angle. Above it is a layer of tuff, a very friable rock which has been weathered out to leave a hollow in the bank below the succeeding rock which is a thin bed of olivine-basalt, above which is the same biotite-andesite mentioned earlier. Making due allowance for irregular dips and flexures associated with proximity to a major fault zone, the dacite sheet cannot be much less than 800 feet in thickness (Pl. III., fig. 3). If it were an intrusion it is difficult to see why contact altera--tion or at least induration of the overlying tuffs should be absent. The dip fault to which the Devil's Punchbowl owes its origin truncates the exposures just described, but as the upthrow is to the east the lower contact of the dacite can be seen less than two hundred/

hundred feet downstream. The underlying rock is a sandstone which shows no sign of metamorphism either in hand specimen or in microsection.

Elsewhere in the area the upper limits of the dacite, where exposed, appear to be either fault junctions or erosion surfaces. It is probable that the earlier surveyors in their interpretation of this rock as an intrusion were impressed by the remarkable manner in which outcrops of great extent and thickness came to most abrupt terminations. In many cases this phenomenon can be traced directly to the operation of powerful strike faults, as for example between Kinclune and Lintrathen. Erosion surfaces can be seen near Cortachy (Pl. II., fig. 3) at the north end of the district and again at Tamhingan (Pl. III., fig. 2) near the Tay. In the old quarry south of the Knock (Cortachy) is exposed an almost vertical surface of dacite, resting against which is an Old Red Sand--stone conglomerate. No contact alteration could be determined in either pebbles or cement. While there remained the possibility of a fault junction, a noticeable feature of the igneous rock is the presence of/

of veins of sediment generally found to be parallel to the fluxion structure. In the quarry, these sedimentary veins are parallel to the junction with the conglomerate. A close search among the boulders of the conglomerate yielded evidence of a conclusive nature. Lying practically on the dacite mass is a boulder which in thin section proved to be identical with it. The boulder is about two feet in one direction and over a foot in the other two and it is fairly well rounded (Pl. III., fig. 1.). The matrix of the conglomerate contains numerous large flakes of biotite, the less weathered specimens of which seem to be optically similar to that of the dacite. Taken in conjunction with the waterworn appearance of the dacite floor there seems to be little room for doubt that the rock is a lava-flow, which was subjected to erosion during Lower Old Red Sandstone times, the larger debris supplying pebbles for the conglomerates while the finer material filled the interstices. Additional evidence to the same effect has been found in the massive conglomerates flanking the Ericht Gorge above Craighall, which contain rounded boulders of/

of the same dacite associated with "Newer Granites"etc.

Elsewhere in this paper is given further evidence for contemporaneous erosion which still more fully explains the apparently capricious occurrence of the Lintrathen dacite, and supplies one reason for the irregularities in the succession of rocks over--lying it.

In habit, the dacite shows in its fluxion structure and in its frequent development of sedimen--tary veins a feature common to many Lower Old Red Sandstone lava flows. In composition it is worthy of note that the dacite shares with the biotite-andesite, which overlies it in the Isla gorge, the peculiar vividly pleochroic black mica which occurs so sparing--ly in any other lava. The only undoubted acid intrusions in the vicinity are the felsite dykes which truncate the Dalradian schists to the north. A number of these were collected and sectioned; they showed no resemblance to the Lintrathen dacite. On either side of the dolerite dykes which cut the Old Red Sandstone, even although the intrusions rarely exceed fifty feet across, slight contact alteration — induration — is noticeable for a short distance, yet nowhere/

nowhere in the vicinity of the Lintrathen dacite have I found fragments of metamorphosed rock not of Dalradian origin. The curious bleached-looking fragments embedded in the upper parts of the rock are of the same nature as the surrounding material and appear to be portions of the early-formed crust broken by the advance of the still partially fluid mass, with which they were incorporated.

In 1886* Durham drew attention to the presence of numerous rather angular blocks of Lin--trathen porphyry associated with water-worn andesites in a conglomerate near Scroggieside Farm at the south end of the Tay Bridge. In 1913 R. Campbell** mapped certain outcrops of this rock in Kincardineshire as lava flows for, although no clear contacts were seen, a similar rock was present as pebbles in higher conglomerates. It is thus clear that the information available from the much more extensive occurrences of the dacite in Perthshire and Forfarshire all points to its extrusive origin.

* "Volcanic Rocks of the North-East of Fife."
Q. J. G. S. Vol. XLII.,p. 423.

** "The Geology of South-Eastern Kincardineshire."
Trans. Roy. Soc. Edin. Vol. XLVIII.p.943.

PETROLOGY of the LAVA FLOWS.

As the rocks vary considerably from rather acid to basic types their mineral assemblage includes many of the common rock-forming varieties, the general characteristics of which will be described first, then the structures to which they contribute, and finally the classification of the rocks themselves, together with their sequence in the field.

Minerals.

Quartz occurs as a primary constituent only in the dacite of Lintrathen. While in elongated vesicular cavities it approaches idiomorphism and has often developed pyramidal facets at both ends, in the main body of the rock it is more commonly deeply corroded and cracked. It is clear and glassy with inclusions of tiny colourless apatite needles and more rarely flakes of biotite.

The felspar content of the rocks varies from sanidine to labradorite. Sanidine is present only in the dacite where it occurs as small strips either untwinned or simply twinned on the Carlsbad law.

Oligoclase/

Oligoclase has a fairly widespread development among the more acid types such as the dacite and the mica-andesites. As phenocrysts it has an elongated tabular habit, the regularity of the periphery being broken by corrosion bays. The crystals are sometimes broken and recemented. Inclusions of glass and apatite needles are not plentiful. Twinning is on the Carlsbad and Albite laws and produces rather thin twin lamellae. As a constituent of the groundmass, oligoclase has the same slender lath-like shapes common to the other plagioclase-felspars. Oligoclase-andesine is the porphyritic felspar of some of the biotite-andesites, appearing as large tables with corroded borders. Inclusions of glassy material, which is sometimes pale grey green and sometimes brown, are abundant; apatite needles are of less frequent occurrence. In the microporphyritic biotite-andesites, oligoclase-andesine is present as elongated laths some three or four times larger than the felspar of the groundmass. Andesine is of widespread occurrence, especially in the pyroxene-andesites. As phenocrysts, it has the same tabular habit and corrosion /

corrosion borders as those already described. Strong cracks transverse to the long axis of the crystals are perhaps more frequently seen. Inclusions are certain--ly much more prominently developed than in the more acid felspars, and take the form of strings of circular and oval glassy material and numerous acicular colour--less apatites. The tabular labradorites of the most basic rocks display an extraordinary history of crys--tallisation and resorption, some zones within the periphery being of a spongy structure. They contain abundant inclusions of glass and black iron oxide. The deep cracks in the felspar are occupied by iron oxide but this belongs to a later stage in the consoli--dation history of the rocks. Cross and stellate twins are of common occurrence in some of the basalts. All the plagioclase-felspars show very strong zoning, the composition of the periphery approaching that of the groundmass felspar.

The biotite of the dacite and mica-andesites occurs porphyritically as large idiomorphic plates, the regularity of its shape being broken partly by resorption and partly by movements which have crumpled and frayed out/

out the ends of the lamellae. It is deeply coloured and vividly pleochroic, $\mathfrak{a}$ = light yellow, $\mathfrak{b}$ = yellowish brown, $\mathfrak{c}$ = dark shellac brown, and it possesses a large optic axial angle. Inclusions of clear apatite needles are almost invariably present. In some of the more compact rocks, the micropheno--crysts of biotite occur as elongated strips and plates largely pseudomorphed by black iron oxide. The mica of the groundmass of these rocks is commonly developed as small irregularly shaped flakes associated with grains of black iron oxide. Their pleochroism varies from brown to almost colourless. Decomposition of the biotite yields chlorites and iron oxide.

Hornblende is found only in the porphyritic biotite-andesite, where it is represented by roughly idiomorphic pseudomorphs composed of either calcite or chlorites or an intimate mesh of both. The rim of the pseudomorphs is clearly defined by black iron oxide, and traces of the original amphibole lattice cleavage are marked by the same mineral. Within this cleavage net the calcite and chlorites have a radiating fibrous development, in which the normal cleavage/

cleavage of the carbonate, which might be mistaken for that of hornblende, is not developed.

Hypersthene is a common porphyritic constituent of many of the lavas, where its idiomorphic outlines, but slightly resorbed, can be recognised. Cleavage is well defined and longitudinal sections nearly always show strong transverse cracks. In colour it is pale green to grey, and pleochroism is not usually very marked. The decomposition of the hypersthene yields fibrous green bastite, often with pronounced pleochroism.

The monoclinic pyroxene is a very pale green augite, the rims of which are sometimes darker than the core. Twinning is common in porphyritic crystals, and zoning and hour-glass structures are frequently noted. It is, however, most commonly developed as a groundmass constituent where its habit is tiny prisms and granules. Its decomposition product is apparently always calcite.

Olivine is the most frequent former of phenocrysts in the basic rocks but no trace of the original mineral has been found in any section. The pseudomorphs/

even-grained, and it is possible with the aid of a lens to discriminate between many of them in the field.

Fluxion structure is very widely developed, but is often only visible under the microscope, where it is evidenced both by the orientation of the pheno--crysts and the arrangement of the groundmass material. Glomeroporphyritic aggregates of both felspars and ferromagnesian minerals are of common occurrence, and occasionally the pyroxene phenocrysts are really polysomatic groups of small crystals. As has been mentioned in the previous section, resorption of the earlier formed constituents and the production of a heavy black iron oxide rim is frequently seen.

The groundmass is partly crystalline and partly glassy the actual ratio of the one to the other varying within very wide limits. In the compact mica-andesites the base is pilotaxitic, con--sisting of tiny felspar laths fluidally arranged with little or no glass. The hyalopilitic structure of Rosenbusch, in which the groundmass is composed of tiny plagioclase strips and augite prisms woven together into a felt, the interstices of which are occupied/

occupied by glass, is very commonly seen in the porphyritic pyroxene-andesites. In some of these rocks, however, especially near the top of the volcanic series, the cooling has been so rapid that the phenocrysts are embedded in a brownish glass clouded with dusty iron oxide. The groundmass of the Lintrathen dacite can best be described as micro--felsitic, varying from glassy to cryptocrystalline. In the groundmass of some of the olivine-basalts the felspar is in sub-ophitic relationship to the augite.

Xenoliths are not of infrequent occurrence in the lava flows, and they fall naturally into two types. In the extremely acid Lintrathen dacite, as will be described in greater detail later, there are many fragments of foreign rocks, all of Highland origin and varying in size from pebbles three inches in diameter to tiny grains visible only under the microscope. On the other hand the olivine-basalts and pyroxene-andesites are in some cases characterised by numerous quartz grains about which is developed a band of very small pale green augite prisms, generally with a radiate disposition from the contact surface, and/

and in every respect similar to the "augite eyes" so well known in the Carboniferous olivine-basalts.*

That one origin of the xenoliths along the Highland Border was some "Newer Granite" mass, is shown by the occasional association of other granite minerals with the quartz. Practically all the quartz grains are devoid of strain shadows which might suggest that none of them had been derived from schistose grits, but on the other hand it is possible that recrystal-lisation may have since taken place and obliterated any optical anomalies.

Classification of the Lava-Form Rocks.

The basis of classification here adopted is the nature of the felspars, and where there is a marked difference between those occurring porphyri-tically and those in the groundmass, the variety last mentioned was taken as the criterion as in most cases there is more felspar in the groundmass than among the phenocrysts.

Excluding/

* Mem. Geol. Survey, "The Geology of Eastern Fife", 1902, pp. 390, 401 - 404.
"The Igneous Geology of the Burntisland District", Trans. Roy. Soc. Edin. Vol. LIII., 1924, p.483.

Excluding sanidine which has a restricted extent, the felspars are oligoclase, oligoclase-andesine, andesine, and labradorite, and in accordance with the general usage rocks with groundmass labradorite are termed basalts while those characterised by the less basic felspars were included in the andesite family. On this classification, taking into account the general rock texture, the minerals occurring as phenocrysts and those forming the groundmass, we have the following eleven rock types.

<u>Andesites.</u>

<u>Porphyritic</u>	Quartz-andesite or Dacite.	1.
	Biotite-andesite.	2.
	Andesine-pyroxene-andesite.	3.
	Labradorite-pyroxene-andesite.	4.
<u>Microporphyritic</u>	Biotite-andesite.	5.
	Pyroxene-andesite.	6.
	Olivine-andesite.	7.
<u>Nonporphyritic, compact</u>.	Biotite-andesite.	8.

<u>Basalts.</u>

<u>Porphyritic</u>	Olivine-hypersthene-basalt.	9.
	Olivine-basalt.	10.
<u>Microporphyritic</u>	Olivine-basalt.	11.

Porphyritic Andesites.

1. Lintrathen Type Dacite.

This rock, known as the Lintrathen porphyry, is described by Teall in his "British Petrography" (1888),* but a description of a closely similar rock from a breccia in the vicinity of the Tay Bridge was published by Judd in 1886 in the Appendix to Durham's paper already mentioned,** and in it reference was made to the Lintrathen variety. As its mineral assem-blage and chemical composition show it to be a dacite, according to the established usage of petro-graphic nomenclature it ought to be termed a dacite of the Lintrathen type (Pl. XIV., fig. 1.).

It is conspicuously porphyritic in deeply corroded and cracked quartz. Of rather more capricious development is the felspar, which is strongly zoned plagioclase, mainly oligoclase. It is commonly corroded, but not to so marked a degree as the quartz. Small strips of simply twinned or untwinned/

* pp. 128, 286.

** "Volcanic Rocks of the North-East of Fife", Q. J. G. S., Vol. XLII., p. 427.

untwinned sanidine occur but are never in great quantity. Biotite occurs plentifully as a porphyritic constituent, and as inclusions in the quartz and plagioclase phenocrysts. The groundmass is generally compact and is characterised by well-marked fluxion structure. It is composed of tiny fragments of quartz and minute felspar laths, often forming a granular mosaic, with apatite and iron oxide as accessories. Brownish glass in greater or less quantity is always present and is accompanied by the growth of spherulites, often with quartz as a nucleus, especially near the upper surface of the flow (Pl.XIV. fig. 2). Differential cooling is indicated by the occurrence of streaks of glass throughout the ground--mass mosaic, and also surrounding the phenocrysts. In a few cases crystals of hypersthene have been found. Throughout there are disseminated small flakes of muscovite, the occurrence of which in a rock of this type appears to be unique. The mica is confined to the groundmass and does not occur as inclusions in the quartz and plagioclase phenocrysts, so that it is possibly of later formation than the biotite./

biotite. In many sections muscovite is absent, in others, particularly near the bottom of the flow, it is abundant. Garnet is another peculiar constituent somewhat scantily represented. An outstanding feature of the dacite is the presence of numerous pebbles of mica-schist, phyllite, schistose grit, and quartzite, which are especially abundant in some cases near the base. The nature and disposition of these xenoliths, indicative of the passage of the dacite flow over an area where was accumulating the wastage of a "Highland" hinterland, renders it not altogether impossible that the muscovite flakes are really foreign to the igneous rock, having been picked up in transit. It is a matter of some difficulty to prove this in a rock whose proper constituents show such extensive cracking, crumpling and fraying, which often give to the dacite an almost pyroclastic appearance.

Below is given an analysis of the Lintrathen dacite recently made by W. H. Herdsman of Glasgow. For comparison there is quoted one of a dacite from Lassen's Peak, California, which is slightly different mineralogically in that the felspar is andesine and the/

the ferromagnesians include hornblende; and also the average composition of dacites based on 30 analyses.

	Lintrathen Dacite.	Lassen's Peak Dacite.	Average Analysis of 30 Dacites*
SiO_2	68.90	68.72	66.91
Al_2O_3	14.54	15.15	16.62
F_eO	2.49	1.76	1.33
Fe_2O_3	1.04	1.16	2.44
MgO	1.08	1.28	1.22
CaO	2.15	3.30	3.27
Na_2O	3.31	4.26	4.13
K_2O	3.83	2.78	2.50
H_2O $105^{\circ}C+$	0.90	0.74	1.13
H_2O $105^{\circ}C-$	0.90		
TiO_2	0.28	0.31	0.33
P_2O_5	0.14		
MnO	Nil.		
Ni & Co	Trace		0.12
S	Nil.		
CO_2	0.32	0.30	
Total	99.88	99.76	100.00

* from Osann, Rosenbusch, compiled by Daly.

2. Biotite-Andesite.

This is a rock with abundant phenocrysts of oligoclase-andesine, and numerous large flakes of biotite. Less important numerically are idiomorphic crystals of hornblende, clots of augite, and occasionally hypersthene. The groundmass consists of small, stout crystals of oligoclase and apatite needles set in a brownish glass crowded with minute specks of iron oxide — hyalopilitic structure, (Pl. XIV., fig. 3.).

3. Andesine-Pyroxene-Andesite.

The porphyritic constituents are andesine, hypersthene, and augite. They are of large size and are scattered fairly abundantly throughout the rock. The groundmass is typically hyalopilitic, consisting of andesine, augite and dark glass with apatite and iron oxide.

There are different rocks included within this type for the relative proportions of the por--phyritic constituents vary in different localities while remaining consistent in any one stretch of outcrop, (Pl. XV., fig. 3.).

4. Labradorite-Pyroxene-Andesite.

The rock contains abundant phenocrysts of labradorite, hypersthene, and augite set in a groundmass which varies from hyalopilitic to glassy, and contains laths of andesine, prisms of both augite and hypersthene and the usual accessories. Occasionally some pseudomorphs after olivine occur, (Pl. XVI.,fig 1).

Microporphyritic Andesites.

5. Biotite-Andesite.

This is a microporphyritic rock in which the phenocrysts are both small in size and few in number. They consist of oligoclase-andesine in narrow laths, often replaced by a calcite mosaic in which some fragments of the original felspar remain, and elongated strips and plates of biotite largely pseudomorphed by iron oxide. The groundmass is strongly felspathic and possesses a trachytic appear--ance, the constituent minerals being oligoclase, biotite, and calcite which probably replaces a little granular augite. The apatite of this rock is the rather large, striated variety already described, (Pl. XV., fig. 1.).

6. Pyroxene-Andesite.

This rock is microporphyritic in hypersthene, often with polysomatic aggregates of granules, and contains fewer monoclinic pyroxenes. Occasionally some serpentinised olivines are present. The ground--mass consists of andesine with pronounced fluidal structure, numerous small prisms of hypersthene and some augite. Instead of glass, this rock has most frequently interstitial areas of fibrous green chlorites. Where the felspars are less regularly arranged the groundmass possesses pilotaxitic structure, (Pl. XVI., fig. 2.).

7. Olivine-Andesite.

Small idiomorphic serpentinised olivines, together with a scanty development of augite, are the microporphyritic constituents. The groundmass is typically basaltic in appearance, consisting of felspar laths and augite prisms with good fluxion structure, but the felspar is andesine. There may or may not be a little brownish glassy residue.

In some cases these rocks carry, in addition, some small plagioclase phenocrysts, which are nearer andesine than labradorite in composition, (Pl. XVI., fig. 3.).

Nonporphyritic Andesite.

8. Biotite-Andesite.

This is an exceedingly fine-grained rock, predominately felspathic, with tiny strips of oligoclase fluidally arranged, among which occur irregularly shaped flakes of brownish biotite, none of them ever attaining any great size. Small prisms and granules of augite occur in great abundance, although in many cases only calcite remains. Apatite is particularly abundant as an accessory. There is much secondary silicification throughout this rock type, (Pl. XV., fig. 2.).

Porphyritic Basalts.

9. Olivine-Hypersthene-Basalt.

A strongly porphyritic rock with numerous large phenocrysts of labradorite, hypersthene, and olivine, set in a groundmass which is composed of small stout rather acid labradorites, olivine and hypersthene, together with granular calcite which may represent original augite. Apatite and iron oxide are plentiful and there is usually present a little glass, (Pl. XVII., fig. 1.).

Porphyritic Basalts. (continued).

10. Olivine-Basalt.

The rock is strongly porphyritic in pseudo-morphs after olivine and tabular labradorite, set in a groundmass of small labradorite laths, calcite remains probably after granular augite, and a few small olivine pseudomorphs. There is an abundant development of iron oxide and apatite. Little glassy residue is seen, but there are numerous irregular cavities occupied by strongly refracting fibrous zeolites, (Pl. XVII., fig. 2.).

Microporphyritic Basalt.

11. Olivine-Basalt.

This is a microporphyritic rock similar in most respects to the porphyritic variety described (No.10), but generally containing interstitial brownish to black glass, often filled with black micro-lites, to a small extent. Fibrous green chlorites occur plentifully in vesicles.

Some of these fine-grained basalts carry small phenocrysts of labradorite in addition to the pseudomorphs after olivine, (Pl. XVII., fig. 3.).

THE SEQUENCE of the LAVA FLOWS.

From a consideration of the general relationships shown to each other by the different lavas in the field, the following sequence has been derived.

Higher Group.

- Microporphyritic Olivine-Basalt.
- Porphyritic Labradorite-Pyroxene-Andesite.
- Porphyritic Olivine-Basalt, and Olivine-Hypersthene-Basalt.

Middle Group.

- Microporphyritic Pyroxene-Andesites and Olivine-Basalts, with Porphyritic Andesine-Pyroxene-Andesite.

Lower Group.

- Microporphyritic Olivine-Andesite.
- Porphyritic Biotite-Andesite.
- Microporphyritic Olivine-Basalt.
- Porphyritic Olivine-Basalt.
- Dacite.
- Compact Biotite-Andesite.
- Microporphyritic Biotite-Andesite.
- Microporphyritic Olivine-Basalt.
- Porphyritic Andesine-Pyroxene-Andesite.

The rocks of the lowest lava group occur in the most northerly part of the Highland Fault area, (Pl. I., figs. 2 and 3), stretching from Bridge of Cally north-eastwards across the Upper Ericht to Auldallan gorge. The highest members of this group form the lowest stratigraphical horizons found in the middle of the Highland Fault area, where the structure has now been found to be in the main a synclinal one pitching out to the north-east (Pl. IV., figs. 2 and 3.). Successively higher lava flows outcrop towards the south-west, and it is there that the members of the middle lava group are encountered. The rocks of the highest lava group occur to the south-east of the syncline but are separated from it by a fault which will be described later. Over part of their outcrop they are folded into a steep anticline.

B. Conglomerates.

The investigation of an area characterised by the presence of lava flows whose stratigraphical constancy could not be taken for granted, and the absence of normal fossiliferous sediments, complicated by a network of faults and possibly also thrust planes, made necessary an examination of the wide-spread/

wide-spread conglomerates. The material was dealt with mainly in the field where the nature of the constituent pebbles and boulders was determined with the aid of a hand lens. In certain cases where accuracy in detail was especially important microscope sections were prepared. For the sake of uniformity some twenty-five pebbles were collected in most cases, but where wide exposures were available three or even four sets were taken separately. On the other hand, certain of the outcrops were so meagrely revealed that a smaller number of pebbles had perforce to suffice.

The aim of this work was threefold -

a. An analysis of the conglomerates to explore the possibility of their use as stratigraphical zones.

b. The recording of any outstanding constituents.

c. An interpretation of the conditions of their accumulation.

The results are interesting in many ways and considerable light has been thrown on problems of the sequence within the area.

In the first place a striking five fold subdivision of the conglomerates is possible.

i. Along/

_i._ Along the northern margin of the Old Red Sandstone area at Bridge of Cally there are basement conglomerates, overlying with marked unconformity the steeply folded Dalradian Schistose Grits, (Pl. V., fig. 1.). These conglomerates consist of vein quartz, quartzites of several colours, schistose grits, phyllites, and mica-schists in great abundance — up to 75%. Less important numerically are hornblende-schists, dark grey andesites or basalts, and a coarse-textured quartz-porphyry. They are considered to be merely local basement conglomerates, an assumption in keeping with the noteworthy absence of variety in their con--stituents, and in accordance with the fact that at certain localities, as for example on the R. Ericht near Old Milton of Drimmie and in the vicinity of Strone House on the R. Ardle, they consist of rather subangular fragments of phyllites lying directly on an eroded phyllite-schistose grit floor. The thickness of these conglomerates, while never very great, varies from place to place.

_ii._ The conglomerates overlying the lower lava flows/

lava flows are essentially volcanic in composition. They consist of generally well rounded boulders of medium to smallish size set in a somewhat granular matrix resembling a sandy tuff, although it is probable that most of the volcanic particles owe their fragmental nature to denudation rather than to explosive eruption. The most striking feature of the conglomerates is the presence of large numbers of rhyolites, generally streaky, often porphyritic in quartz and felspar, and occasionally spherulitic; to a less extent trachytes are present, cream coloured rocks with many tabular felspars and fewer elongated black ferromagnesian mineral remains set in a pale groundmass composed of tiny felspar laths. These highly acid rocks constitute anything from 50 - 100% of the conglomerates, the remaining components being andesites and basalts. The conglomerate forms the hills of Ascreavie, Kinclune, Brankam, Knock of Formal, Inchley, and Balduff.

iii. Interbedded with the middle lava groups are conglomerates still dominantly volcanic in character but with the acid igneous rocks rarely contributing/

contributing more than 25% and the basic igneous rocks showing a correspondingly higher percentage. The boulders show considerable variety in point of size. They are well exposed in the Ericht and its tributaries in the vicinity of Craighall (Pl. V., fig. 2), and are also found to the south-west near the Loch of Clunie and at Craig of Tronach overlooking the Tay.

iv. Associated with and overlying the highest lava flows there are conglomerates composed almost exclusively of basic igneous rocks, which are present as water-worn pebbles varying from two inches to two feet in diameter. They are exposed on the north side of the anticline, referred to earlier, at Clintlaw and Wardend, and more extensively on the southern flank at the gorge of the Slug of Achrannie, at Shanally and further north at Meams..

v. In the highest conglomerate belt (Pl.V., fig. 3,) there is a reversion to material such as characterises the first-mentioned group but the pebbles show much more rounding. Vein quartz, quartzites, and schistose grits constitute, together with/

with a less numerous group of mica-schists and phyllites, fully 70% of the pebbles. The residue consists of red felsite, some dark fine-grained basic andesites or basalts, together with fragments of arenaceous sediments. There is a strong development of interbedded fine-grained sandstones often with small vein quartz pebbles in a well-rounded condition. The overlying rocks are pebbly sandstones of a similar type, but with a steadily diminishing percentage of pebbles as higher horizons in the sequence are reached.

With the exception of the first which is of necessity of limited and sporadic occurrence, these conglomerate belts can be traced throughout the major part of the area and therefore can be used as strati-graphical horizons with a fair degree of confidence provided that the import of those which are almost exclusively Old Red Sandstone in their material — contemporaneous erosion — be not overlooked. There are certain lateral variations which call for mention. The conglomerates overlying the lowest lava group contain the highest percentage of acid volcanic rocks in the district due north of Alyth at Balduff and Inchley/

Inchley Hills; to the north-east there is an increas-
-ing content of less acid varieties, and to the south-west they pass up into the conglomerates associated with the pyroxene-andesite group. This middle lava group passes laterally on its north-eastern margin into volcanic conglomerates but its concealed termina-
-tion to the south-west of Balduff Hill may be due in part to contemporaneous erosion during or after the time of eruption of the flows. The conglomerates overlying the middle lava group are confined to the south-western half of the district and show a diminish-
-ing content of acid volcanic rocks together with an increasing percentage of quartzites, schistose grits, and vein quartzes.

The conglomerates overlying the highest lava flows of porphyritic pyroxene-andesites and basalts, with one slight exception, cannot be traced south-west of the R. Isla as they are lost against a N.E. - S.W. fault, and successively higher horizons are revealed in a S.S.W. direction. Towards the north-east there is an increasing percentage of quartzite and schistose grit pebbles, but beyond the R. South Esk/

R. South Esk basic igneous rocks again predominate. To the south-west a small outcrop of volcanic con--glomerate is seen above the Tay at Stenton. The highest belt of conglomerate, which is so extensively quartzitic at Alyth Hill, becomes a pebbly sandstone in the Kirriemuir district but further north near Memus it is again an assemblage of vein quartzes, quartzites and schistose grits.

A few individual boulders in the conglome--rates are worthy of special reference. Pebbles of fresh biotite-microcline-granite occur in conglomerates which contain a high percentage of "Highland" material — quartzites, mica-schists, etc., — and occupy a horizon above that of the lower lava flows, showing that the denudation of the Highland area to the north and west must have been very rapid in early Old Red Sandstone times to remove the capping of country rock from the plutonic masses.

Another interesting boulder, found in the conglomerate north of Fyall, is an angular weathered fragment of red dolomite fault breccia, such as is typical of the Highland Boundary Fault both in this district/

district, as will be described shortly, and also from other exposures along the same belt. This is note--worthy in that it shows that the rocks of the belt had been subjected to movement before local Old Red Sandstone times.

There are two constituents of many of the conglomerates which by reason of their petrological contrast with the remainder of the igneous material attract attention. One is a coarse-textured quartz-porphyry in which, in addition to the quartz, shining plates of biotite, duller crystals of hornblende, and felspar can be seen readily without the aid of a lens. The other is a reddish felsite nearly always charac--terised by quartz crystals and flakes of biotite. Neither of these rock types occurs in place anywhere within the area and it is suggested that they may be intrusions of early or even Pre- Lower Old Red Sandstone times. Their distribution as pebbles throughout the conglomerates is interesting. The first mentioned rock occurs among the most northerly local basement conglomerates to the extent of 6%. In the second zone, where acid and basic volcanic rocks/

rocks are so well mixed, it forms 15% of the content. Except in the vicinity of Cortachy where it forms 33%, it occurs rather sparingly in the higher volcanic con-glomerates. In the highest belt it contributes less than 6% of the pebbles.

The fine red felsite does not occur to any marked extent in conglomerates of the northern zone. In the accumulations overlying the lowest lava group it constitutes on an average 8%. The conglomerates associated with the pyroxene-andesites contain some-times as much as 30%, but there is a fall to 5% in the highest porphyritic pyroxene-andesite zone. In the highest conglomerates the felsite pebbles amount to 12% of the whole.

The general lowness of the figures for the supply of these two rocks to the conglomerates suggests a limited extent to the outcrop from which they were derived; and the continued supply of these small percentages through so long a period of time would seem to indicate considerable resources to the outcrop — two characteristics of dyke rocks.

Reference has been made already to the discovery of dacite boulders in certain conglomerates and the light thereby thrown on the origin of that rock.

C. Sandstones.

Normal fine-grained sediments are so scantily represented in the lower and middle parts of the Lower Old Red Sandstone sequence that they were examined carefully wherever encountered. No trace of organic remains has been found so far. The rocks have a fairly uniform reddish tint and possess in most cases well-defined bedding planes. Some of the more compact sandstones near Old Milton of Drimmie and also north of the Loch of Clunie have been mapped previously as lava flows.

Under the microscope, the most outstanding feature of the sandstones is the shape of the quartz grains, which are either highly angular or subangular, and which in the majority of cases do not show strain shadows. Flakes of muscovite come next in order of importance. Biotite, which may be either brownish or greenish, is not present in such abundance as the white mica but the flakes are commonly of larger size. Elongated areas of black iron oxide are probably pseudomorphous after biotite. Fragments of basic volcanic rocks occur in every microsection examined/

examined; acid volcanic rocks contributed detritus apparently only during the time of accumulation of the middle sandstone beds. Microcline and oligoclase, generally in a remarkably fresh condition, are found in most specimens. Recognisable fragments of phyllites and other Highland rocks were found in lower and higher parts of the sequence, but not at inter- -mediate horizons. Rather large, striated-looking, apatites and small zircons are the only other note- -worthy constituents of the sediments.

The cementing material, which is often scanty, is most generally calcite. In a few examples a fine volcanic powder fills the interstices between the grains.

Tuffs.

Pyroclastic rocks have a wider development than has been recorded hitherto on geological maps. They occur as comparatively thin beds intercalated among the lava flows and are inconspicuous in the field.

Under the microscope the rocks can be seen to belong to two main types: I. Rocks composed of lapilli/

lapilli with bounding surfaces which may be either convex or concave, and which possess little or no calcareous cement,

and II. Rocks composed of volcanic fragments showing generally convex outlines indicative of rounding by water action, and commonly associated with calcareous cement.

Some of the more glassy fragments show an approach to "aschen structur", but no examples were found to demonstrate this so strikingly as those from the Lorne area described by Kynaston.* The minerals of the tuffs are those of the lavas, but they are commonly in a more advanced state of decomposition which has released a great quantity of dusty black iron oxide to be disseminated throughout the rocks.

The lowest tuffs found are among the lavas immediately overlying the dacite. At Kinaird they are composed of lapilli of fine-grained acid andesites and porphyritic biotite and hornblende-andesites. In some cases the rock is entirely volcanic, in others there is a calcite cement. Another group of tuffs associated/

*Trans. Geol. Soc. Edin. Vol. VIII., 1905, p. 87.

associated with an olivine basaltic flow is strongly basic in character and in most specimens is marked by the development of sandstone veining often with well-defined banding, the material being small angular quartz grains, without strain shadows, and flakes of muscovite and biotite. The same assemblage of material is found in equally fine-grained but much more widely spread sandstone near the local base of the sequence at the junction of the R. Ardle and the Black Water.

The tuffs associated with the lower part of the middle (pyroxene-andesite) lava group consist of rounded fragments of volcanic rocks, of both acid and basic types, together with angular granitic quartz grains, flakes of biotite and less commonly of muscovite. Other pyroclastic rocks immediately over-lying or underlying basic lava flows are composed almost exclusively of irregularly shaped lapilli of olivine-basalt, the interstices in some cases being filled with calcite. Intercalated among the highest porphyritic pyroxene-andesites and basalts are tuffs composed of lapilli of the same rocks with a green cement/

cement which may represent original volcanic dust.

Overlying the highest lavas is a series of what appear to be well-bedded red sandstones. Under the microscope, however, they are seen to consist of angular and subangular fragments of pale acid volcanic rocks strongly felspathic and commonly with fluxion structure, together with a lesser quantity of dark glassy-looking rocks with felspar laths. Angular granitic quartz and broken crystals of fresh acid plagioclase, probably oligoclase, microcline, and orthoclase are present in varying proportions. The mosaic groups of unstrained granitic quartz, occasion-ally noted, were probably associated with the last named minerals in some of the Newer Granite masses. Muscovite and biotite occur both separately and as intergrowths. In a few cases garnets were found.

SECTION VII.

THE SERPENTINE BELT.

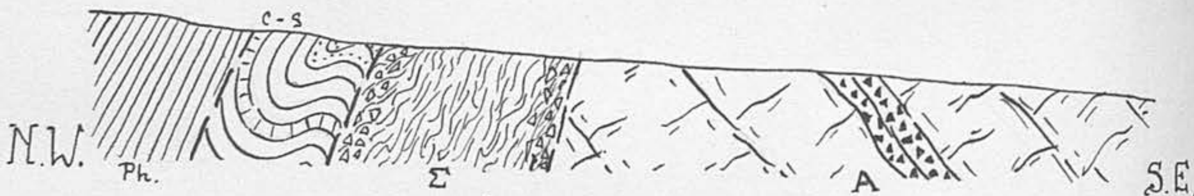
An interesting feature of the Highland Boundary Zone is the occurrence of a belt of serpen--tinous rocks roughly parallel to the edge of the Highlands and traceable with certain breaks for a distance of thirteen miles. Except in the R. Prosen section, the serpentine belt is bounded on both sides by rocks of Lower Old Red Sandstone age but of different stratigraphical horizons. The width of the outcrop varies considerably. In the vicinity of Lintrathen, rocks hitherto mapped as serpentine occur in the direct line of the serpentine belt and show similar relationships to the adjacent Old Red Sand--stone. The present investigation has shown their affinities with rocks of the Spilitic suite in some cases and with the normal serpentines in others.

It is advisable, in view of the subsequent attempt to interpret these occurrences, to give a short description of the exposures of the serpentine belt which are largely confined to stream sections.

Cortachy Sections.

The most northerly exposure is found in a disused quarry south of the Knock of Cortachy. While no contacts with the country rock are seen, the ridge in which the quarry is situated would suggest that the serpentine outcrop has a width of about two hundred feet. Fifty feet to the south-east, across a dry valley, is a second quarry exposing Lintrathen type dacite and a conglomerate. About a thousand feet to the north-west the same dacite gives rise to some Knolls on the edge of the arable land of Craigies Farm. The serpentine, which has a greenish to bluish mottled appearance, is strongly sheared at an angle of seventy degrees in a direction a little north of west. Along the shear planes there is abundant white talc or steatite and in the joint planes fibrous greyish chrysotile is developed.

About a mile to the south-west, just above Cortachy Bridge, the serpentine is exposed in the S. Esk, (Pl. VI., fig. 1.). The rock presents a white to greenish appearance and is very noticeably shattered with the production of ovoid masses. There is a general tendency for the development of rhombohedral/



Scale 1in = 880 ft.

SECTION ALONG R. PROSEN.

Ph = Phyllites with Lenticles of Schistose Grits.

C-S = Chert and Black Shale Series.

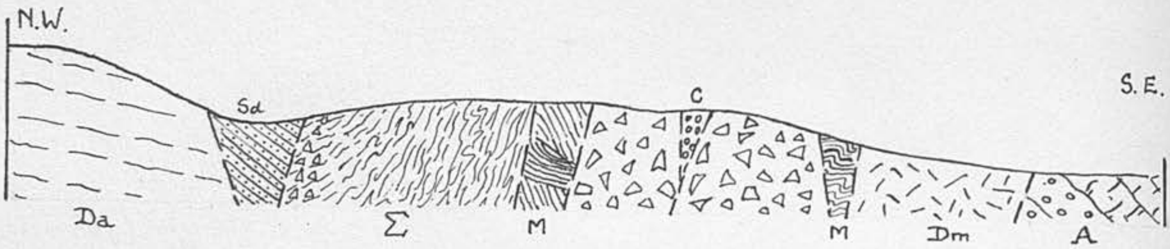
Σ = Serpentine passing on either hand into Fault Breccias.

A = Lower Old Red Sandstone Lavas & Tuffs.

rhombohedral - almost cubic - cleavage. Neverthe- -less it presents rather steep banks to the stream which has been diverted along it for five hundred feet before again turning to the south-east. The outcrop, which is not more than one hundred and twenty feet across, is bounded on the north by a curious reddish granular rock apparently formed of crushed Lower Old Red Sandstone mudstones, similar to those exposed a short distance upstream. To the south there is a gap of some fifty feet beyond which is a Lower Old Red Sandstone conglomerate. The general orientation of the serpentine belt is a little south of west.

R. Prosen Section. (see diagram on opposite page).

The next exposure of serpentine is found in the R. Prosen about a mile to the W. S. W. On the steep north bank opposite Prosenhaugh farm there are several outcrops of serpentine which taken together must be three hundred and fifty feet across. The rock is highly sheared, the planes being almost vertical. Both to the south and to the north is a red-stained dolomite-breccia — a typical fault rock. Upstream/



Scale 1in = 290 ft.

CARITY DEN SECTION.

Da = Dacite Lava.

Sd = Red micaceous sandstones.

Σ = Serpentine passing into Dolomitic-Serpentine-Breccia.

M = Red Mudstones.

C = Conglomerate.

Dm = Dolomitic Fault Rock.

A = Conglomerates & Andesite Lava-flows.

Upstream the northern one passes into a striking breccia with large angular fragments of the red rock, some over two inches across, set in a cement of white and cream-coloured calcite. Beyond this, after a gap of three hundred and fifty feet there is revealed in the stream bed and banks a group of highly inclined graphitic shales, cherts, and quartzites, considered to belong to the Highland Border Series.

Beyond the dolomite-breccia at the southern boundary of the serpentine there are no solid exposures for over thirteen hundred feet, after which lava flows and conglomerates of Lower Old Red Sand--stone age appear on the south bank. The distance between the dolomite-breccias on either side of the serpentine is in the region of seven hundred feet.

Carity Section. (See diagram on opposite page).

The succeeding Carity Den section, about a mile-and-a-half to the south-west is probably the most interesting and instructive. It was described by Lyell in 1825 and was again mentioned in a publication by Judd in 1885. For the moment I shall describe the succession upstream, leaving the interpretation/

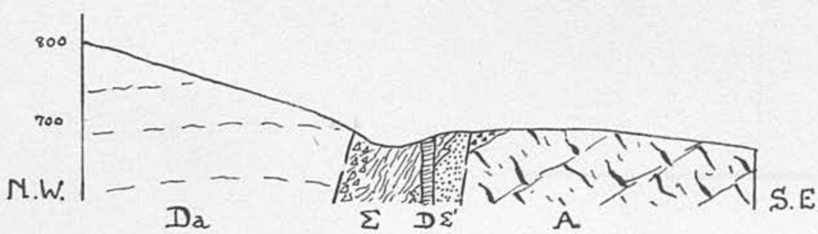
interpretation until all the serpentine exposures have been indicated. South-west of Carroch farm the Carity Burn runs through lavas and conglomerates dipping S. to S. E. Some three hundred and fifty feet above the right-angle bend, the nature of the rocks changes abruptly and in the field to the east red and grey dolomites with strongly marked vertical jointing are exposed. On the west bank of the stream is a red dolomite-breccia. One hundred and thirty feet up--stream, in an old quarry on the east bank, is revealed some red mudstones showing a considerable amount of dislocation and brecciation. While in the absence of fossils the age of these rocks cannot be determined, they show a strong resemblance lithologically to Lower Old Red Sandstone mudstones of which there are good exposures in the neighbourhood. They are inextricably mixed up with a dolomitic serpentine-breccia. A hundred feet to the north, a red dolomite-breccia forms a small cliff. In hand specimen and in microsection this rock is identical with that from the R. Prosen out--crops. Immediately beyond and high up the east bank is the conglomerate/

conglomerate exposure described by Lyell, (Pl. VII., fig. 2.). It consists of a small mass slightly under six feet across. The conglomerate is composed of well-rounded pebbles of quartzites and schistose grits, together with a few vein quartzes, mica-schists, and volcanic rocks. The pebbles often show the shearing so common in many Lower Old Red Sandstone conglomerates. Associated with this are some thin-bedded red mudstones and coarser grained sandstones. The mass is apparently vertical and shows signs of slickensiding. To the north the red dolomite-breccia again appears and can be traced for over a hundred feet, after which, beyond an almost vertical junction, there is a further exposure of sediments. These are thin-bedded red mudstones showing marked dislocation, shearing, and slickensiding. The uppermost ten feet dip downstream at a very high angle; directly underneath them is a second ten feet of similar rock but with a gentle dip downstream; and below is exposed about three feet of the same rock with a steep dip downstream. The figures just given indicate the depth of the cliff exposure and not the thickness of the sediments, (Pl. VII., fig. 1.).

The/

The succeeding thirty feet to the north is a hollow cut back into the river bank and is covered with vegetation. Beyond rises a steep wall of highly slickensided serpentine, the jointing and shearing being in an almost vertical direction, (Pl. VI., fig. 2.). In colour the serpentine is dark green and it is often characterised by shining areas of bronzite. White talc occupies the joint planes and coats many of the surfaces. Near the south end of the exposure is a very coarsely crystalline variety of serpentine composed almost entirely of large fibrous bronzite crystals, (Pl. VI., fig. 3.). After some two hundred and thirty feet of serpentine the red dolomite-breccia is again exposed forming a small but conspicuous cliff.

For the next thirty feet upstream turf con--ceals the bed rock, and then appears an outcrop of micaceous red sandstone followed after an interval of eighteen feet by thin-bedded red mudstones. Both these sediments dip downstream at an angle of about 40°. They show marked and rapid variation in texture from bed to bed, contain abundant mica flakes, and are characterised by ripple marks and rain pits. The section/



Horizontal Scale 1in = 880ft.
Vertical Scale 1in = 250ft.

KINCLUNE SECTION.

Da = Dacite Lava-Flow.

Σ = Serpentine passing North into Breccia.

Σ' = Schalstein.

D = Dolerite (Tholeiite) Dyke.

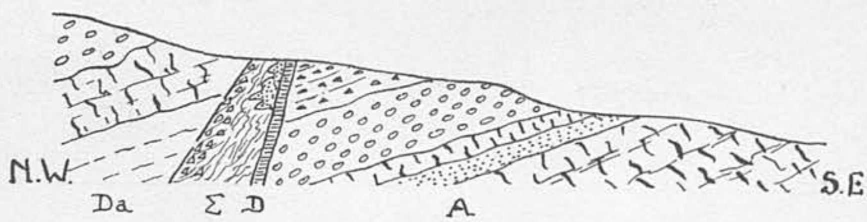
A = Pyroxene Andesite & Tuffs.

section is completed by the outstanding mass of Lintrathen type dacite through which the Carity Den has been cut. Unfortunately no contact between the igneous rock and the mudstones was found.

The Carity exposures from the micaceous sandstones on the north side of the dolomite-breccia last described to the conglomerates downstream from the most southerly dolomites are over a thousand feet long.

Kinclune Burn Section. (see diagram on opposite page).

There are no exposures for the next three and a third miles. In the Kinclune Burn west of Muir of Holm is mapped a small serpentine outcrop but an investigation of the section has shown some of the rocks to possess different characteristics to those previously described. Beginning from the main road and tracing the sequence upstream, the first outcrops are of coarsely porphyritic pyroxene--andesites and tuffs. Seventy feet upstream is a very small exposure of a curious bluish grey rock, strongly sheared. Under the microscope it is seen to/



Scale 1 in = 880 ft.

MELGAM WATER SECTION.

Da = Dacite with overlying Basalt & Conglomerate.

Σ = Serpentine with Schalstein in upper part stippled.

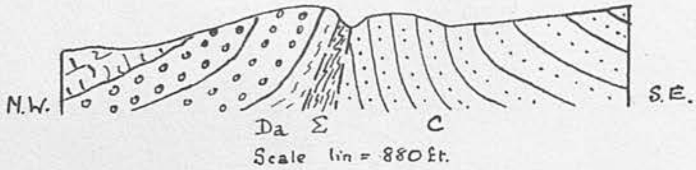
D = Dolerite (Tholeiite) Dyke.

A = Lower Old Red Sandstone Lavas & Sediments.

to be of pyroclastic origin, resembling the schal-steins commonly associated with lavas of the spilitic suite. After a short gap devoid of rock exposures a little waterfall can be seen to be due to a dolerite dyke intersecting the stream-course almost at right angles. For the next two hundred feet the somewhat scanty outcrops consist of red dolomite-breccia, with fragments of serpentine replaced by carbonates and studded with red-brown picotite grains. The section ends with the Lintrathen type dacite which forms the rounded hill on which Kinclune House stands.

<u>Melgam Water Section.</u> (see diagram on opposite page).

In the Melgam Water at Kinaird, a mile and a third to the south-west from the Kinclune Section, is a short exposure – ninety feet in all – bounded on the south by a dolerite dyke beyond which, after five hundred feet of alluvial flats, a Lower Old Red Sandstone group of lavas and conglomerates appears. North of the dyke and on the left bank is a group of highly sheared rocks with an almost vertical dip. Against these the dolerite dyke shows marked chilling. Although/

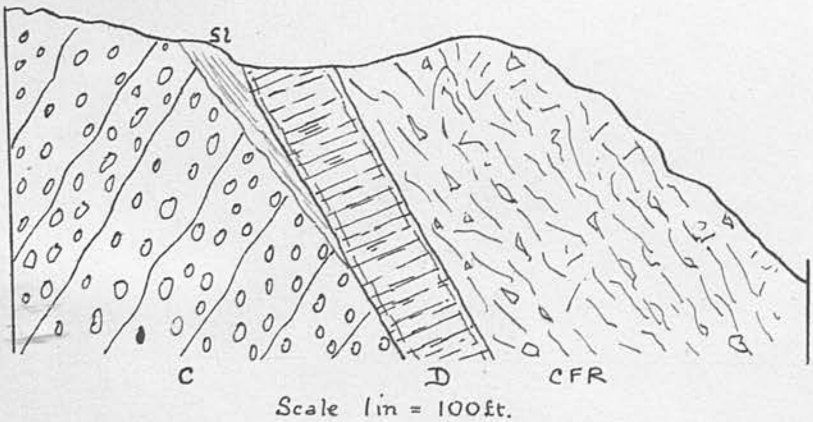


Fyall Section.

Da = Dacite-flow with overlying conglomerate & lava.

Σ = Serpentine.

C = Conglomerate & Sandstones.



Limestone Bank Section.

C = Old Red Sandstone Conglomerate.

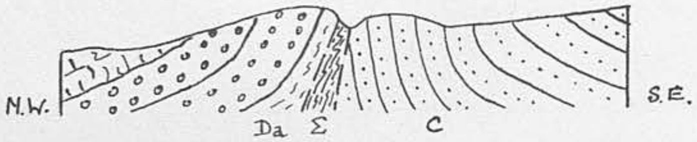
D = Dolerite (Tholeiite) Dyke.

CFR = Calcareous Fault Rock.

Sl = Sheared Fault Rock.

Lower Old Red Sandstone, so that the dyke must occupy a line of fault.

To the south-west of the R. Isla, and to the north of Easter Craig farm, serpentine outcrops in the fields and is accompanied on its south-east flank by red dolomite-breccia, the whole mass dipping very gently to the N. N. W. Other outcrops including a beautiful grey crystalline dolomite occur in the neighbouring fields to the south-west. Immediately across the main Glenisla road, a broad gently rounded valley stretches W. S. W. to Bamff House, and along its southern slopes are numerous exposures of massive green serpentine with large glistening crystals of bronzite. There is an apparent northerly dip at a very low angle. Large boulders of serpentine have accumulated along the valley floor. The narrowing westerly termination of this hollow is Burnieshed Den on both sides of which the serpentine is well exposed, although nowhere can contacts with any other rock be seen. The serpentine belt at this locality cannot be less than five hundred feet across.



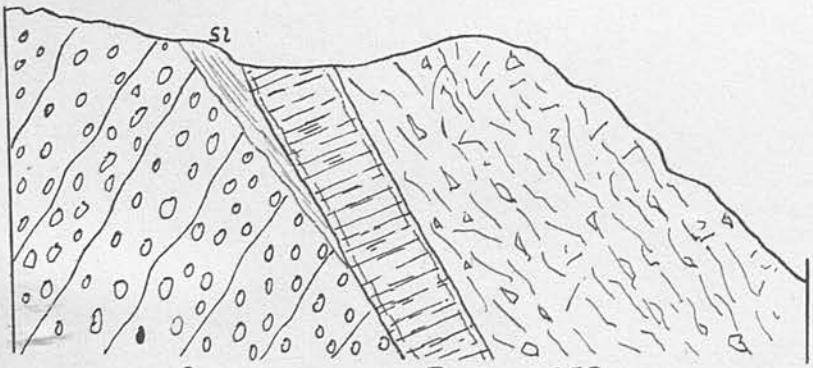
Scale 1in = 880 ft.

Fyall Section.

Da = Dacite-flow with overlying conglomerate & lava.

Σ = Serpentine.

C = Conglomerate & Sandstones.



Scale 1in = 100 ft.

Limestone Bank Section.

C = Old Red Sandstone Conglomerate.

D = Dolerite (Tholeiite) Dyke.

CFR = Calcareous Fault Rock.

Sl = Sheared Fault Rock.

Fyall Section. (See diagram on opposite page).

A mile and a quarter to the south-west in the tributary west of the Alyth Burn at Fyall, a new exposure of brecciated serpentine has been found. Upstream is an outcrop of steeply inclined Lintrathen type dacite: downstream across a lateral valley is a conglomerate made up largely of vein quartz and quartzites.

Loch of Clunie Section. (see diagram on opposite page).

The only remaining serpentine exposure is about eight and a half miles to the south-west, at Limestone Bank quarry at the south-east corner of the Loch of Clunie. At the present time a dolerite dyke some forty five feet thick is being quarried for the supply of road metal, but over a hundred years ago an adjacent site yielded Limestone for agricultural purposes. Some of this rock still remains, particu--larly at the west side of the dyke. From its extraordinarily shattered nature, its variable com--position, and the angular foreign material scattered throughout its mass on the one hand, and the absence of any signs of stratification and any trace of organic/

organic remains even under the microscope on the other, there seemed to be no room for doubt that it was a fault rock. The bounding walls of the dyke, which is inclined to the north-west, are, as is commonly the case, highly slickensided at an angle of 60° to the north-west, (Pl. VIII., fig. 1.). On the east side of the intrusion the fault breccia itself shows strong shear planes set at an angle of 50° to the north-west. The rocks to the north and west are lavas and conglomerates relatively low down in the Lower Old Red Sandstone sequence, while to the east and south are quartzite conglomerates and sandstones of a higher stratigraphical horizon. In the Edinburgh Journal of Science* there is a paper by MacCulloch dealing with the Clunie limestone which he visited "a long time" prior to the publication of his observations in 1824. His descriptions are most valuable and helpful as subsequent quarrying, refuse dumping, and the spread of vegetation have obscured most of the outcrops of his day although new exposures are now available. MacCulloch recognised that the Clunie/

* Ibid, Vol. I., 1824, p.1, "On the Limestone of Clunie, in Perthshire, with remarks on Trap and Serpentine."

Clunie Limestone was no ordinary stratified rock and concluded that it was "lying in an oblique direction with regard to the schist and the conglomerate ....accidently intruding at the place where these two more regular rocks meet." The argillaceous schist, which he describes and indicates on his sketch map, is not now visible and I can only suggest that the rock was a small inlier of Dalradian schists, for Lower Old Red Sandstone rocks occur on the west and north sides of the loch, or a very large erratic block. While he notes the brecciated nature of the limestone, the "mutual penetration" of limestone and conglomerate along their line of contact, and states that the deficiency in connection between the schist and the conglomerate may arise partly from the form of the ground, partly from the disturbance which attends the trap vein, and perhaps also in some degree from the casual occurrence of the independent cal--careous rock, there is nothing in the text to show that he regarded the exposure as a fault junction.

Special attention is paid to the steatite--serpentine zone 6 - 12 inches wide, which is limited to/

to the contact of the dyke with the limestone, and while the author believes that there is gradation between the dolerite and the serpentine, he must have forestalled later workers in the field of metamorphism by his statement that the serpentine is probably the result of some combination between the different substances at their point of contact. The production of serpentine from the contact alteration of so impure a limestone as that of Clunie would be unquestioned in the present state of our knowledge, and I am inclined to regard it as being of a widely different age to the massive serpentine exposures earlier described.

SECTION VIII.

INTERPRETATION of the SERPENTINE BELT.

The work of MacCulloch described at the end of the last section is apparently the earliest recorded investigation of the Highland Border Serpentines (1824). A year later Lyell published a paper "On a Dike of Serpentine, cutting through Sandstone, in the County of Forfar,"* which dealt with especially the Carity Den section, and which contained the first mineralogical description of the rocks together with a detailed survey of their relationships to the surrounding strata. As it is on the results of this investigation that the intrusive nature of the serpentine with regard to the adjacent Lower Old Red Sandstone rocks has been maintained, it is important to consider the evidence.

In the first place Lyell refers to the red Breccia occurring at the northern margin of the serpentine on the left bank of the Carity Burn and likens it to red shale altered by a trap dyke. A little/

* Edin. Journ. of Science, Vol. III., 1825, p. 112.

little to the south are contorted sandstone and shale "which must evidently be considered as entangled in the dyke" (of serpentine) — p. 116. Yet on the following page he states that the sandstones to the south of the major serpentine outcrop (and yet <u>in</u> the serpentine belt according to both his mapping and my own) do not present any decided indications of being altered by the contact of the serpentine. The red breccia immediately to the south of these sedi--ments he calls an indurated siliceous sandstone and remarks that it "has every appearance of being an altered rock." Of the exposure of conglomerate which he observed was flanked by dolomitic serpentine, he states that it is evidently much altered as the quartzose pebbles are split and are reunited by ferruginous matter, a feature of a similar conglomerate on the R. Isla, and which he suggests may be due to the heat of the igneous rock. A little further on, however, he says "that the conglomerate ..... on the Carity has, in this instance, been altered by the neighbourhood of the dolomitic serpentine cannot be with certainty affirmed."

Up/

Up to this point, then, Lyell is doubtful of any contact alteration having been effected in those rocks which can be identified readily as normal sediments. The present investigation has produced no evidence either in the field or under the micros--cope of thermal metamorphism in them. With regard to the rocks in which Lyell did recognise alteration, it has been found that they are red dolomite-breccias which have been derived largely if not entirely from serpentine, microsections revealing typical serpentine mesh structures pseudomorphed by carbonates, and quantities of picotite identical with that character--istic of ordinary serpentine. Brecciation is common and the dislocation planes are occupied by shattered serpentine pseudomorphs, carbonates, and secondary silica. The alteration is conspicuous but is partly hydration and oxidation and partly crushing - both phenomena associated with faulting not contact metamorphism. The unaltered serpentine in the Carity is highly sheared with a steep dip to the north-west, and it passes both upstream and down--stream into dolomitic serpentine fault breccias which/

which separate it from typical Lower Old Red Sandstone rocks but of widely different horizons. To the north is the dacite which is fairly low in the sequence, while to the south are the porphyritic pyroxene--andesites with which the surface vulcanicity of the district closed. It is noteworthy that the breccia zones are of great thickness, being 60 feet to the north of the serpentine and 650 feet to the south, which would seem to indicate faults of considerable magnitude.

There remains for consideration the relation--ship of the normal sediments, mentioned above, to the serpentine itself. No definite contact alteration has been noted, although in one case a group of laminated red mudstones might be considered to be very slightly harder than usual, possibly due to infiltra--tion of mineral matter in solution, but the difference between these rocks and others from different localities is too minute to justify speculation regar--ding its origin. Their outstanding feature is the extraordinary variation of the dip, practically from horizontal to vertical, and the presence of planes of movement/

movement with slickensiding, both suggestive of fault relationships with the surrounding serpentine or dolomitic serpentine-breccia. In lithological character these sediments are in no way different from exposures of Lower Old Red Sandstone age in the vicinity. The mass of conglomerate is lying in an almost vertical position in the red dolomite-serpen--tine-breccia, and is associated with red sandstones. The pebbles are in most cases sheared quartzites, but in neither the cement which binds them together nor the sandstones was there any trace of induration or alteration. The conglomerate closely resembles one interbedded with the highest Lower Old Red Sandstone lava flows on the Carity about a mile to the east and, while it may not be its counterpart, there are many others, generally of a fairly high horizon among the conglomerates, of similar composition as regards both cementing material and pebbles. The splitting of the pebbles to which Lyell and Buckland drew attention is by no means confined to the vicinity of igneous rocks, being a common feature of the Highland boulders in most of the Lower Old Red Sandstone conglomerates/

conglomerates, while it is not present in pebbles of that period. The shearing is presumably the result of Pre-Old Red Sandstone crustal movements and not of Post Old Red intrusions. I am therefore of the opinion that all the evidence obtained in the field and under the microscope indicates that the junctions between the serpentine and the adjacent rocks in the Carity section are in every case fault planes.

Before proceeding to the relationship between the serpentine and adjacent rocks elsewhere in the area, it must be mentioned that Lyell visited most of the exposures and noted that while the sediments to the east "are cut off at an angle and are evidently disturbed, the dyke of serpentine itself pursues its course uninterruptedly in a direct line for many miles." Impressed by the altered rocks associated with the true serpentines, by the split pebbles of the conglomerates, and by the fact that it truncates the stratified rocks, he concluded that the serpentine "is therefore not of contemporaneous origin, but, like the greenstone with which it is connected, of posterior date." In 1875 Judd visited the Carity exposures under/

under the guidance of Lyell and accepted his conclu--sion that the serpentine produced marked alteration on the rocks which it traverses. (Q. J. G. S. p. 399). Finally Sir A. Geikie in "The Ancient Volcanoes of Great Britain" (1897) refers to the "intrusive dykes of serpentine" (p. 293) and with regard to their age says, "......there is no evidence to connect them with the volcanic phenomena of the Old Red Sandstone. Not improbably they belong to a later geological period."

As no direct contacts with any other rock are seen in the serpentine quarry at the Knock (Cortachy) discussion of its probable relationships will be left for the moment. The South Esk serpentine has nearly vertical shear planes in it and is bounded on the north steeply by a crush of Lower Old Red Sandstone mudstones. To the south is a conglomerate probably high up in the sequence. The Prosen serpentine is vertically sheared, is bounded by fault breccias of the usual type, and separates rocks of the Highland Border Series from lava flows of the highest Lower Old Red Sandstone volcanic zone. The Carity Den sections which have been so fully described come next in/

in order. The serpentine-schalstein exposures in Kinclune Burn are limited to the north by a dolomitic fault breccia and like the Carity serpentines separate the dacite of a comparatively low horizon from the highest lava group of porphyritic pyroxene-andesites. In the Melgam Water is the corresponding serpentine-schalstein mass, the most northerly exposure of which is a red dolomite-breccia. To the north is an olivine-basalt overlying the dacite, to the south a volcanic conglomerate immediately above the highest lavas of the district.

The exposure of this important belt of rocks in the R. Isla is in one sense unfortunately scanty. There is no serpentine and very little trace of fault breccia. A dolerite dyke, the common associate of this zone, is present and marks a nearly vertical plane of strong dislocation, for to the north is the sandstone underlying the dacite horizon while to the south but a short distance away is the olivine-basalt which is the latest lava flow of Lower Old Red Sandstone age along the Highland border. The Incheoch serpentine differs from the others described/

described in showing a comparatively gentle foliation dip to the north, and in the absence of a breccia exposure in that direction while one outcrops to the south. From topographical peculiarities and the sudden termination of serpentine and dolomite-breccia exposures beyond Easter Craig farm, it is thought probable that the dip fault affecting the Lintrathen dacite at the Devil's Punchbowl likewise shifts the outcrop of the serpentine, but no solid rock was found between the farm and the R. Isla to the east.

Above Burnieshed of Bamff Den, on the hill slope to the south, the serpentine outcrops with a gentle northerly inclination of its shear planes. It separates the acid volcanic conglomerate overlying the dacite horizon from the highest vein quartz and quartzite conglomerate zone. This is the last serpentine outcrop of any size and is indeed the southern termination of the serpentine belt shown on the Geological Survey Map, Sheet 56, but a new set of exposures has been found in the Alyth Burn near Fyall Mill, about a mile-and-a-quarter to the south-west, and also in a tributary streamlet still further south-west./

south-west. A typical carbonate-serpentine-breccia occurs separating a sheared mass of Lintrathen type dacite from the vein quartz and quartzite conglomerate to the south. Incorporated in the breccia are angular and shattered fragments of schistose grits.

For the distance of a mile to the south-west the line of dislocation coincides with a broad and deep U-valley, the Den of the Welton, beyond which it is apparently responsible for the truncation of the Glenballoch microporphyritic hypersthene-andesite, the east-west ridge of which forms the southern boundary of Drimmie moorland. In the banks of the R. Ericht there are no solid exposures but there can be no doubt that the marked recurved bend above Craighall Bridge, and the striking cone-fronted pile of the Heughs o'Mause are both due to the presence of this important fault line which separates a volcanic conglomerate on the north from well-bedded pebbly sandstones outcropping below Craighall Bridge. A little further to the south-west, in the Lornty Burn below Milton of Drumlochy, is a breccia intervening between a volcanic conglomerate and a porphyritic lava of/

of the highest group, which with another underlying conglomerate is truncated to the south-east by a second line of fault well exposed along the southern shore of the Suicides' Pool.

The next significant exposure is the fault breccia already described from the Limestone Bank Quarry at the south-east corner of the Loch of Clunie. The available evidence at present shows it to be a calcite-dolomite-breccia steeply truncating a quartzite conglomerate of a fairly high Lower Old Red Sandstone horizon to the south-east. While no contact is observable to the north-west, there are lava flows and conglomerates of a lower horizon less than a quarter of a mile away to the west. MacCulloch mentions the presence of phyllites (clay slate) but I have been unable to find any outcrop in the vicinity, the nearest being at Baldornoch, nearly two miles to the north-west. The fault breccia contains sheared fragments of volcanic rocks both of Lower Old Red Sandstone types and of others resembling spilites, and is especially characterised by the presence of shear-planes inclined at an angle of from 45° to 55° from/

from the horizontal in a direction almost due north-west (N. 40. W.). Although the junction with the conglomerate is rather obscure, it would appear to be closely related to the direction of these shear-planes. A second plane of movement at a slightly steeper angle produced a slickensided-walled fissure up which rose a dolerite dyke some forty five feet wide, with transverse columnar jointing. This is the best exposure in the area for demonstrating the direction of hade of the fault, which is seen to be an overthrust from the north-west.

A little over a mile to the south-west the calcareous fault rock used to be quarried at Cairnmuir. A second fault rock of a similar nature has been worked at Stralochy further to the south-west and presented a problem at first in that the slicken-sided surface dipped at 50° to the south-east, and that there can be very little downthrow between the quartzite conglomerate to the west and the pebbly sandstone to the east. There is, however, a much greater break in the succession a quarter of a mile to the west of Stralochy, where the strongly porphyritic/

porphyritic andesites and basalts of the highest group are faulted against the microporphyritic hypersthene--andesites of a lower horizon. The line of dislocation follows the hollow west of Thornton and truncates the lower andesite group with the formation of the great craig feature known as Kemp's Hold, overlooking the Tay. The fault is nowhere exposed on the north bank of the Tay, owing to the presence of alluvial flats, but it is most probable that the right angle bend of the river there is a direct result of the occurrence of the dis--location plane, which is accompanied in the case of every river along the Highland Boundary belt by similar sharp flexures in its course.

Having established the fact that the southern boundary of the Serpentine Belt is everywhere a most important fault line which can be traced far beyond the limits of the Serpentine exposures, and having indicated that the somewhat scanty evidence points to the disloca--tion being a steep upthrust from the north-west, there remains for consideration the northern boundary of the serpentine. Where exposures are available it has been shown that the presence of fault breccias leaves no doubt/

doubt that there, too, a plane of movement has truncated the exposures. In this case, however, as the rocks to the north are with one exception (the R. Prosen section) of Lower Old Red Sandstone age the fault must be a normal one with a downthrow to the north. Of the two, the second fault is the less important as it apparently dies out at intervals, a phenomenon exhibited in the R. Isla section where the one fault present throws down to the south-east. It is interesting to note that this is the structure across the serpentine belt in the Aberfoyle district deduced by T. J. Jehu and R. Campbell.* The serpentine thus behaves like a horst, except that the south-eastern boundary is a thrust plane and not a normal fault. The well-marked shearing of the serpentine, while parallel to the direction of the bounding faults, is also parallel to the direction of the main Caledonian folding, and as it must be older than the Lower Old Red Sandstone to be truncated as described and to permit of the infaulting of Lower Old Red Sandstone sediments in the Carity Den exposures, it is only reasonable to ascribe its initial foliation/

* Trans. Roy. Soc. Edin., Vol. LII., 1917, pp. 206 - 208.

foliation at any rate to the Pre- Old Red Sandstone crustal movements.

A second fault line is marked on the Geological Survey Map separating the Lower Old Red Sandstone lavas from the Dalradian schists, for the first part of its course, from Stenton on the Tay, passing three-and-a-half miles north of Blairgowrie, a mile north of Lintrathen, and appearing on the R. Prosen a little upstream from the serpentine belt. While there are no good exposures of the fault plane, the presence of thick dolomite-breccias closely resembling the Limestone Bank rock together with the fact that the younger rocks are invariably found on the southern side and that rather steep folding has been recorded from the northern one, all lend weight to the supposition that it too is an upthrust from the north-west. On the north side of Balduff Hill there is an exposure of a rock which is so highly decomposed as to make its iden--tification very difficult. While it may be a weathered specimen of the adjacent fine-grained acid andesites, there is a suggestion of variolitic structure such as the spilites often exhibit. If it is a spilite there must be a small horst there similar to the serpentine one to the south.

PETROLOGY of the SERPENTINES and SCHALSTEINS.

Serpentine rocks are sufficiently attractive in appearance and peculiar in composition to have received the attention of petrologists early in the history of geological investigation, and the exposures of the area have formed the subject of several publica--tions included in the list on p. 8 . The general literature on serpentines seems to indicate that the nature of the principal varieties has been fairly well established as a result of the labours of Professor Bonney and to a less extent those of Sir J. J. Teall. An up-to-date summary of the characteristics of the serpentines of the Lizard by Sir J. S. Flett is to be found in the memoir of the Geological Survey of England and Wales, "The Geology of the Lizard and Meneage", (1912), p. 61, and of some of the Highland Border Serpen--tines by Prof. T. J.Jehu and Dr. R.Campbell in "The Highland Border Rocks of the Aberfoyle District", Trans. Roy. Soc. Edin., Vol. LII., 1917, p. 195. The most recent publication on the Forfarshire serpentines is Judd's paper in Vol. XLI of the Q. J. G. S. (1885), "On the Tertiary and Older Peridotites of Scotland".

In/

In hand specimen the serpentines of Perth-shire and Forfarshire vary from massive rocks with gleaming crystals, sometimes fully a quarter of an inch long, set in a dark green compact matrix to highly sheared types with white or bluish surfaces and ramify-ing veins of talcose material.

Under the microscope the rocks are seen to be altered exceedingly, the only fresh minerals present being enstatite and picotite. While three distinct varieties have been recognised, they apparently grade into one another, there being no evidence to suggest that they do not all belong to the same igneous mass.

I.

In the most common variety of serpentine there are disseminated throughout the rock large roughly tabular crystals of a colourless mineral with well-marked cleavage. The extinction is very often parallel to this cleavage, but sometimes slightly oblique extinction has been recorded. The mineral being optically positive the evidence identifies it with Enstatite, although occasionally the double refraction is unusually high. In one microsection several transverse/

transverse sections were observed which possessed the 010 and the prismatic cleavage planes. Serpentinisa--tion there apparently took place more readily along the prismatic cleavage planes, the centre being occupied by very fine fibrous chrysotile with rather low double refraction. Beyond this another type of serpentine characterised by stronger double refraction extends a variable distance into the pyroxene, but its fibres are developed parallel to the pinacoidal cleavage. The residual cores of unattacked enstatite are subsequently replaced by serpentine of very low double refraction, and, to judge by the apparent homogeneity usually dis--played, by one continuous process. Where the rhombic pyroxene is pseudomorphed by very pale green fibrous serpentine with low double refraction giving slate blue tints under XN, it is possible that we are dealing with longitudinal sections in which the complex cleavage would not be visible, (Pl. XVIII., fig. 1.).

The boundaries of the enstatite are well--marked even after serpentinisation, and it is in apparent porphyritic relationship to the remainder of the rock. The outlines of the pyroxene are most frequently curvilinear, convex towards itself, which may/

may be due to resorption or on the other hand it may be evidence of late formation in the vicinity of earlier formed granular minerals. As, however, the enstatite not uncommonly occurs in glomeroporphyritic aggregates the individuals of which show, by their cleavage, different orientation, this would indicate a freedom of growth and synneusis supporting the contention that they are phenocrysts.

The pyroxene phenocrysts are set in a matrix of darker green serpentine showing the mesh structure characteristic of olivine replacement. A fine dust of black iron oxide is scattered throughout the reticula--tions and, even after all the serpentine has been substituted by carbonates, perpetuates the mesh pattern and facilitates the determination of the rock. As has been recorded elsewhere, the cores of the olivine net--work are often clouded by segregation of black iron oxide particles, being darkest towards the centre. The serpentine occupying the cracks has a medium double refraction while that in the cores has a low double refraction and sometimes approaches isotropism. The olivine would appear to have had originally a somewhat granular/

granular habit similar to that in the dunite of Balsam Creek, of which I possess a section.

Dark reddish brown picotite is invariably present in rather small lozenge-shaped crystals. The irregular cracks and the rims of the crystals are con--spicuous with black iron oxide. While it sometimes occurs within the pyroxene, picotite is more commonly associated with the mesh (olivine) serpentine, even having regard to the preponderance of the last mentioned mineral in the rocks.

Taking into account the minerals and structures of the serpentine described, it seems most suitable to designate it a Porphyritic Enstatite-Olivine-Serpentine derived from a rock of the Harzburgite type. I have been unable to find any diallage in these rocks so that Judd's use of the term Lherzolite for them is not permissible.

II.

The second variety of serpentine has the same mineral assemblage as the first but is characterised by an overwhelming preponderance of enstatite pseudomorphs of unusually large size - sometimes over half/

half an inch in length, (Pl. XVIII., fig. 2.). These constitute more than three fourths of the rock and the scanty intervening areas are occupied by fibrous chrysotile and a little mesh serpentine. The general appearance of this rock recalls most strongly the segregations of some of the larger intrusive masses, and the resemblance is still further emphasised by the strings and clots of picotite or chromite which, by their resistance to weathering, form well-defined dark streaks standing out in strong relief on the pale sur--face of the outcrops. Similar bands, but generally of larger dimensions, have been described from the Lizard serpentines and also from among the Tertiary igneous rocks of Skye.

III.

The remaining type of serpentine is a rather fine-grained rock which appears to be non--porphyritic. Under the microscope it is almost entirely composed of mesh serpentine. A little lattice serpentine suggestive of pyroxene is present together with the usual accessory picotite. In view of the predominance of olivine-serpentine, this rock is best described as a <u>Dunite-Serpentine,</u> (Pl. XVIII., fig. 3.).

SCHALSTEINS.

The most outstanding characteristic, micros--copically, of the non-serpentinous sheared rocks from Kinclune Burn and Melgam Water is their tuffaceous aspect. They are composed of discrete fragments of igneous rocks, many of which are brownish-black in colour, speckled with black iron oxide and containing ghosts of tiny felspar laths and what may be ferro--magnesian remains. These are set in a fine matrix which shows clearly-defined "aschen" structure, irregular concavo-convex areas occurring throughout the mass and filled with fibrous green chlorites, specks of black iron oxide, and some secondary quartz which may approach idiomorphism, (Pl. XIX., figs., 1 and 2.). Silicification of these rocks is fairly general. Calcite seems to have been developed at a later stage and is limited to patches, veins, and cracks. Streaks of black iron oxide or of reddish haematite often follow the main lines of the "aschen" structure. The remains of variolitic structure were noted in some slides.

The rocks do not resemble any of the Lower

Old/

Old Red Sandstone tuffs described earlier. They are so highly decomposed that no vestige of their original mineral composition remains, but structurally they seem to possess affinities with the ashes of the spilitic suite, the schalsteins. No trace of the picotite which is the invariable associate of the serpentine rocks was found anywhere. While the microporphyritic ferromagnesian remains are in keeping with a Lower Old Red Sandstone assemblage, the differences between these sheared rocks and those of Lower Old Red Sandstone age, their close association with the serpentine, and their participation in the same shearing movements, taken together weigh the balance in favour of their Pre- Old Red Sandstone age. From the general inclination of the shear planes or folding axes to the north-west in both stream sections it would appear that the schalsteins dip under the serpentine. The presence together of the coarse-textured serpentine which is probably a rather deep-seated intrusion and the tuffs, may indicate that the former was actually intruded into the later, but the intense dislocations have so far baffled any attempt to gain definite field evidence of the nature of/

of their relationship. Spilites have been described from other parts of the Highland Boundary associated with fossiliferous sediments which fixed their strati-graphical horizon as Upper Cambrian. Sediments of probably Upper Cambrian age have been discovered in the R. Prosen valley as has been described in an earlier part of this paper, but they are unaccompanied by igneous rocks, (See Section V.).